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Three-Dimensional Characterization of X-ray Refractive Optics

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Compound refractive lenses (CRLs) are versatile optical elements in synchrotron hard X-ray science (E > 15 keV). They are used to create X-ray nanobeams and to magnify images of e.g. crystal grains [1, 2]. CRLs differ significantly from lenses for visible light. The refractive index for X-rays is smaller than 1, hence X-ray focusing lenses have a concave rather than a convex shape. Low-Z elements (Be, Al, Si) are used to reduce absorption that competes with refraction. The refractive power of a single lens is small, hence they are compounded into arrays of up to several 100 single elements; and more severely they have radii of curvature (ROC) in the lower micron range. Also, to account for spherical aberration, the ideal shape is approximated as parabolic. Planar Silicon technology allows integration of a multitude of 1-dimensional-focussing Silicon CRLs onto single chips and offers great freedom in lens design [3].

We fabricated Silicon CRLs at DTU Danchip, the cleanroom facility of the Technical University of Denmark, by UV lithography, deep reactive ion etching (DRIE), and surface smoothening by thermal oxidation with subsequent etching of the grown Silicon oxide layer with hydrofluoric acid. The most challenging process is DRIE, whereas the main target is to achieve close to 90° sidewalls along the whole feature in order to guarantee lens uniformity. The features are basically cavities in the form of parabolic cylinders with radii of curvature of ~6 µm, lateral dimensions of ~100 µm × ~50 µm, depths of ~120 µm, and local aspect ratios exceeding 10 (Fig.1a and 1b).

Here, we characterize the three-dimensional shape of the fabricated single lens elements in order to allow optimizing the manufacture independent of expensive tests at a synchrotron facility. Knowledge of the exact shape of the lenses enables understanding of their optical performance in an actual experiment. The uniformity of the ROC along the depth of a lens is an important figure of merit, since a respective deviation would result in non-uniform focal lengths and hence in a distortion of the focused X-ray beam.

The straightness of the sidewalls can be fast and easily measured by cleaving the wafer and inspecting cross sections of the etched features with a confocal optical profiler (OP). A negative taper of -0.4° is observed at a large portion of the sidewall of the lens (Fig. 2). OP relies on reflected light captured by the used objective and hence the maximum detectable slope is limited. At the apex of the structure the slopes of the parabolic sidewalls become too steep to map an extended region with OP. Actually, the data obtained with our instrument is limited to a region of ~6 µm around the apex, corresponding to a z-range of only ~3 µm, which is not enough to reliably determine the ROCs. Therefore, we use an atomic force microscope (AFM) and its full z-range, which potentially enables measuring a region of up to 26 µm around the apex. In contrast to the region measured by OP, the very apex is positively tapered with a sidewall angle of +0.4°. Fits of the measured profiles reveal a continuous increase of ROC from the top to the bottom of 6.2 µm to 6.7 µm (Fig. 3). We interpret the different sidewall tapers at different regions of the features and the linear increase of the ROC over the depth as a consequence of aspect ratio dependent etching.

Furthermore, we molded negative replicas of the cross sections of the fabricated lens chips in PDMS, which facilitates the AFM measurements (Fig. 1c). On the one hand, intrusions are turned into protrusions, thereby overcoming the limitation of commercially available AFM tips trying to penetrate shallow and deep cavities (Fig. 4). On the other hand, lenses fabricated with different etch recipes can be integrated onto a single sample, which avoids the need of multiple alignments of different samples in the microscope. We investigated the reliability of the molding procedure and obtained consistency between measurements made on the replica and the master regarding the overall shape, taper, ROCs and surface roughness.

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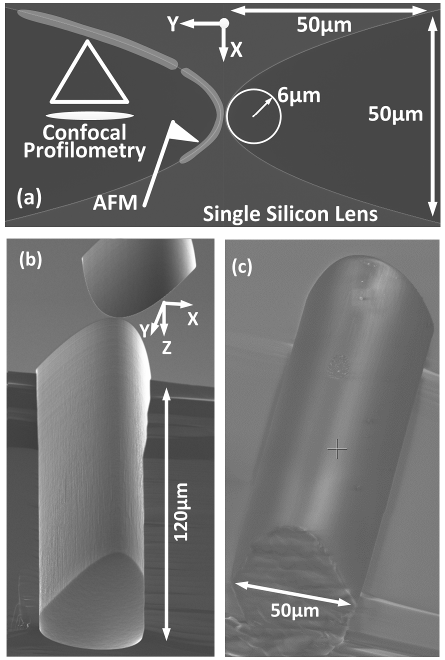

Fig. 1. Scanning electron micrographs of (a) a lens top view including dimensions, axes notations, and measured regions, (b) a cleaved Silicon CRL, and (c) a negative replica of a lens in PDMS.

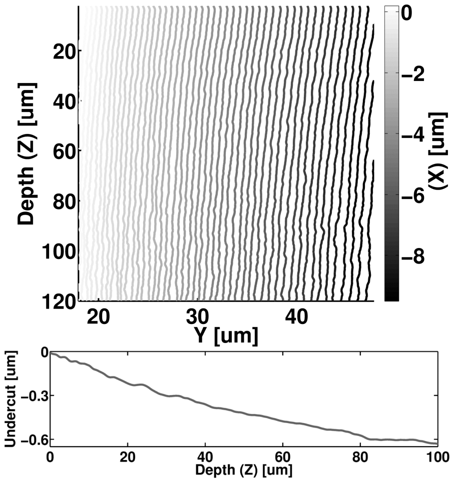

Fig. 2. Contour plot of a Silicon lens sidewall obtained by OP and the respective average profile along the depth showing a negative taper of -0.4°.

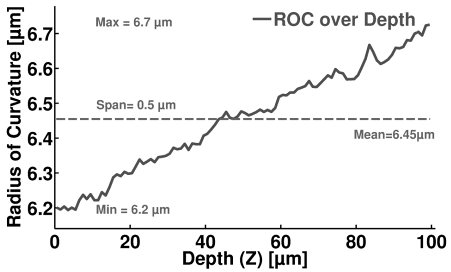

Fig. 3. Variation of the radius of curvature of the parabolic profiles along the depth of the Silicon lens features.

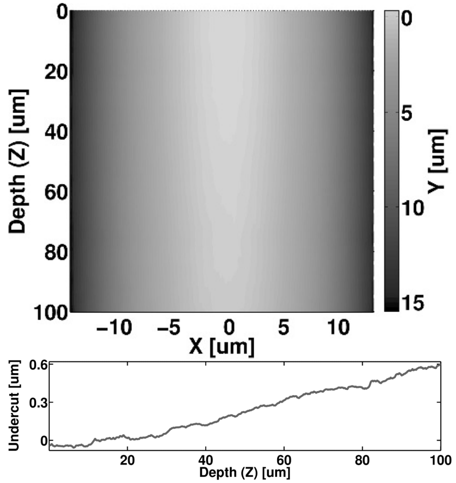

Fig. 4. Surface plot obtained by AFM at the apex of a parabolic PDMS cylinder and the depth profile at X = 0 µm showing a positive taper of +0.4°.